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A CRUSTAL MODEL AND ITS TECTONIC IMPLICATION ON THE EVOLUTION OF THE PACIFIC MARGIN OF THE NORTHERN ANTARCTIC PENINSULA

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Abstract: The Shackleton Fracture Zone (SFZ) and the South Shetland Trench (SST) are prominent bathymetric structures in the Southeast Pacific off Antarctic Peninsula. The SFZ comprises a high ridge and a deep trough. The SFZ ridge was probably formed by the uplift of low-density material like serpentinite. Two phases of deformation observed in the trough suggest that (1) a large-scale crustal faulting due to transtensional movement along the SFZ during Drake Passage opening before 6 Ma formed the deep trough, and (2) recent contractional structures around the trough are indicative of the present convergence between the Scotia and Antarctic plates. The angle of subduction of oceanic crust in the SST increases from southwest to northeast along the SST as its age increases from southwest to northeast. Because thick accumulation of sediments is not expected in active trenches with a horst and graben structure, the presence of thick trench-fill sediments (up to 1300 m) over a horst and graben structure in the South Shetland Trench (SST) indicates that they accumulated after the cessation of subduction at about 4 Ma.

key words: Shackleton Fracture Zone, South Shetland Trench, crustal model, tectonic evolution, Antarctic Peninsula

1. Introduction

Off the northern tip of the Antarctic Peninsula, two distinct bathymetric features are observed (Fig. 1). The SFZ is one of the most prominent geological structures in the Southern Ocean. Its pronounced ridge 2000 m high above the seafloor extends about 800 km from north of the Antarctic Peninsula to the southern margin of South America. The SST which reaches depths of greater than 5000 m lies offshore of the northern margin of the South Shetland Islands. The islands in turn are separated 200 km from the northern Antarctic Peninsula by Bransfield Strait.

The SFZ is an indicator of the initial direction of the Drake Passage opening (BARKER and BURRELL, 1977; CUNNINGHAM *et al*., 1995). The fracture zone is the western boundary between the Scotia plate and the Antarctic and former Phoenix plates. Seafloor spreading between the Antarctic and former Phoenix plates to the west of the SFZ continued until about 4 Ma while seafloor spreading in the western Scotia plate to the east stopped at about 9 Ma (BARKER, 1982; LARTER and BARKER, 1991). The distinct SFZ ridge probably was formed by the different procedures of seafloor spreading at both sides of the SFZ. The

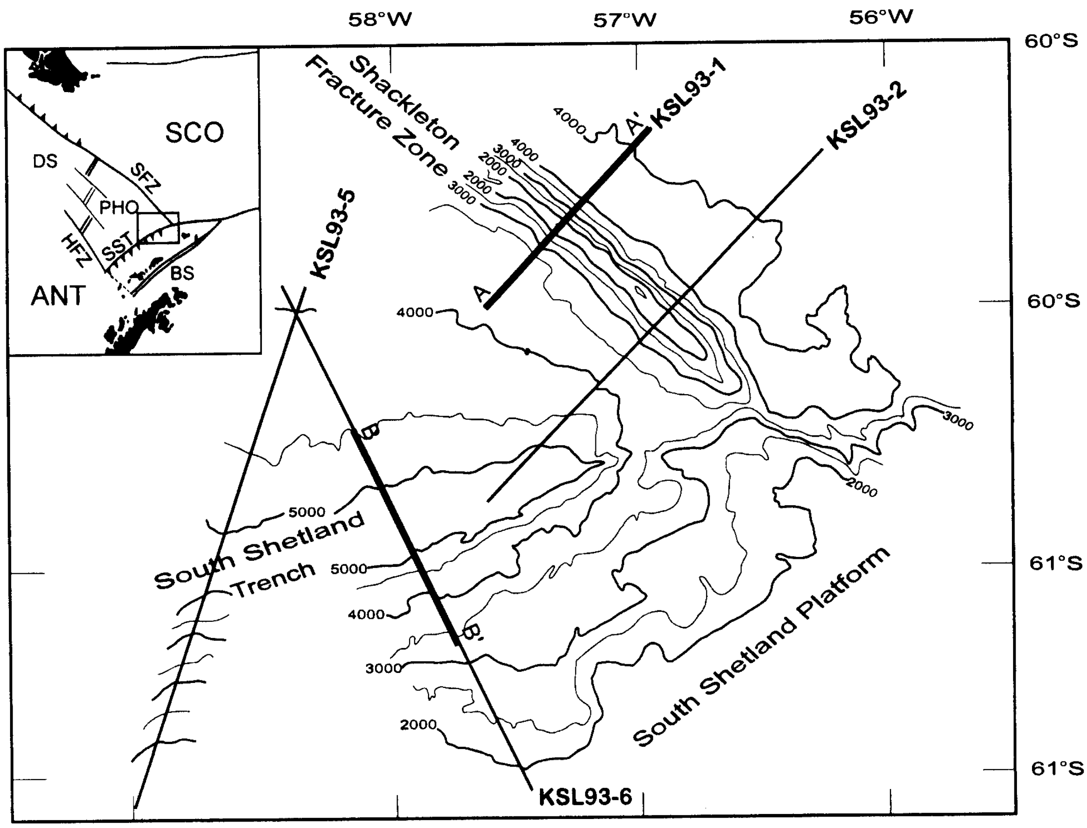


Fig. 1. *Location Map with geophysical survey lines in the study area. Contours show regional bathymetry with 500 m contour interval. The bold solid lines indicate seismic reflection profiles in Figs. 3 and 5. Inset map shows regional tectonic setting, and the location of main map is indicated with a box. ANT = Antarctic plate, BS = Bransfield Strait, DS = Drake Passage, HFZ = Hero Fracture Zone, PHO = former Phoenix plate, SAM = South America plate, SCO = Scotia plate, SFZ = Shackleton Fracture Zone, SST = South Shetland Trench.*

present-day plate motions between the Antarctic and the Scotia plates are largely accommodated by left-lateral strike-slip motion along the SFZ (FORSYTH, 1975; PELAYO and WIENS, 1989). Crustal structure of the SFZ is still unknown for its important role in tectonic evolution of the western Scotia Sea.

According to seafloor magnetic anomalies in the southeastern Pacific, successive ridge-trench collisions occurred northeastward along the Pacific margin of the Antarctic Peninsula from some 50 Ma to 4 Ma (BARKER, 1982). After each collision, both spreading and subduction ceased in the concerned plate segment. Consequently the trench topography collapsed and the margin became passive. The last remaining segment of trench structure (SST) and the last major remnant of the former Phoenix plate lie between the Hero and the Shackleton Fracture Zone (BAS Tectonic Map of the Scotia Arc, 1985).

In this study, multichannel seismic and gravity profiles obtained in the SFZ and SST area (Fig. 1) are interpreted focusing on structural deformation in the oceanic crust and overlying sediments and deep crustal structures of the SFZ and the SST. These results provide an important clue in relation to the plate dynamics in the southern Scotia Sea and the northern Antarctic Peninsula.

2. Data Acquisition and Processing

The MCS were obtained with a 96-channel analog streamer. Each channel consists of 24 hydrophones and the group interval is 25 m. An array of 16 guns with a total volume of 22.6 liters was used as an energy source. Shot interval was 50 m and sampling rate was 4 ms. Acquired MCS data were processed by conventional processing procedures with GEOVECTEUR® (CGG) software.

The gravity data were obtained with a Lacoste-Romberg marine gravity system (model S) with a gravity difference of 0.1 mgal. The raw gravity data were recorded together with time, position, water depth, ship speed, and ship direction. Basic corrections, including the drift, latitude and Eötvös corrections, are compensated to obtain observed gravity anomalies.

3. Shackleton Fracture Zone

3.1. *Anomalous crustal structure of the SFZ*

The free-air anomaly is dominated by the attraction of the topography, hence two distinct structures, a SFZ ridge and a deep trough (Fig. 2) control the gravity profiles of KSL93-1 and KSL93-2. The profiles show positive gravity anomaly of about 130 mgal over the ridge and negative anomaly of about 10 mgal over the trough. Although topographic effect would be removed, these observed gravity values over the ridge and trough seem to be rather small. It suggests the presence of low-density material there.

It is well known that major marine fracture zones with large transverse ridges have very anomalous structures beneath the fracture zones. Based on seismic refraction data, DETRICK *et al.* (1993) demonstrated very anomalous structure of North Antarctic fracture zones having thin, lower-velocity crust and the broad upwarping of the Moho beneath the fracture zones. Therefore we determined to refer to DETRICK *et al.*'s results as a prior information for gravity model of the SFZ because there have no other studies for the SFZ. From the assumption of the thin crust beneath the ridge we deduced the lower-density ridge to fit the observed gravity anomaly.

The resultant gravity models show a low-density ridge of 2.45 g/cm^3 and a narrow zone of thin crust beneath the SFZ ridge. The Moho shallows by 2.5 km beneath the ridge. The crust becomes thick from the ridge to both ends of the profiles, ranging from some 3 to 6 km in thickness. These models are similar with the crustal model for the Vema Fracture Zone proposed by PRINCE and FORSYTH (1988) and North Atlantic fracture zones compiled by DETRICK *et al.* (1993). Although the density of the sediments and the depth of the trough can not be deduced exactly from our gravity and seismic data, the gravity low associated with the trough can be attributed to the relatively low-density sediments (1.9 g/cm^3) filled in the trough (3 km deep).

3.2. *Formation of the SFZ Ridge*

The southern end of the SFZ is distinguished by a prominent submarine ridge about 2000 m higher than the surrounding sea floor (Fig. 1). On seismic profile KSL93-1, the SFZ ridge is almost symmetrical in shape without sedimentary cover (Fig. 3). The SFZ ridge is typical of transverse ridges that are found in large fracture zones, which run parallel

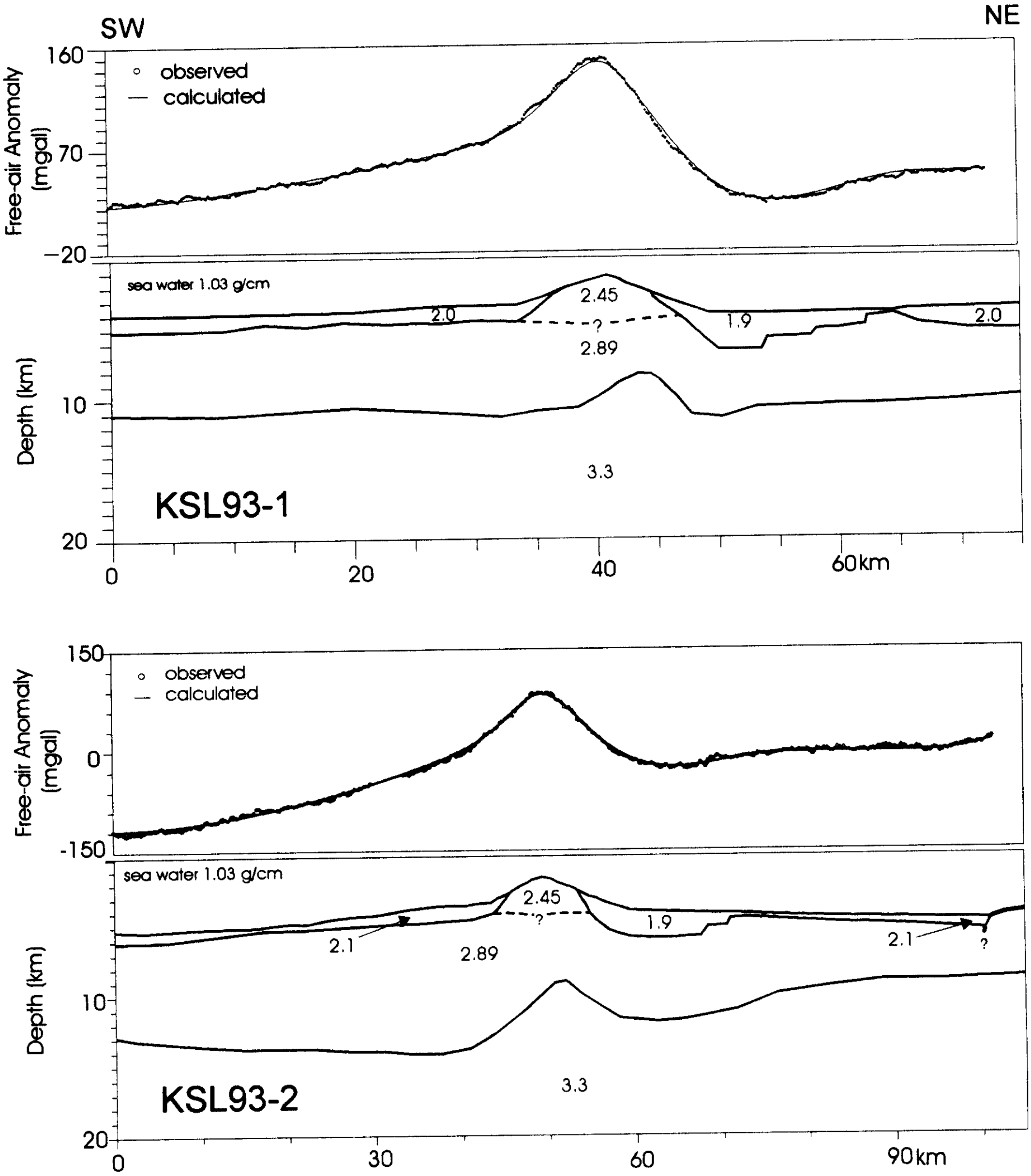


Fig. 2. Gravity models for KSL93-1 and KSL93-2 across the Shackleton Fracture Zone, suggesting the narrow zone of thin crust concentrated beneath the serpentinite ridge and thick sediments filled in the trough.

to the main transform fault-zone valley (BONATTI, 1978). Gravity models of KSL93-1 and KSL93-2 suggest the presence of low-density material forming the ridge (Fig. 2). Among the lower-density materials, serpentinite with a density of about 2.45 g/cm^3 is thought to be the most acceptable material considering the origin of the ridge, because serpentinite is the most widespread rock type of a typical transverse ridge (BONATTI, 1976; LOUDEN *et al.*, 1986). Although numerous hypotheses on the creation of the ridge have been proposed, its origin is still controversial (BONATTI, 1976; AUZENDE *et al.*, 1989; CANNAT *et al.*, 1991; HENRIET *et al.*, 1992).

On seismic profile KSL93-1, the age (22 Ma) of the oceanic crust of the former

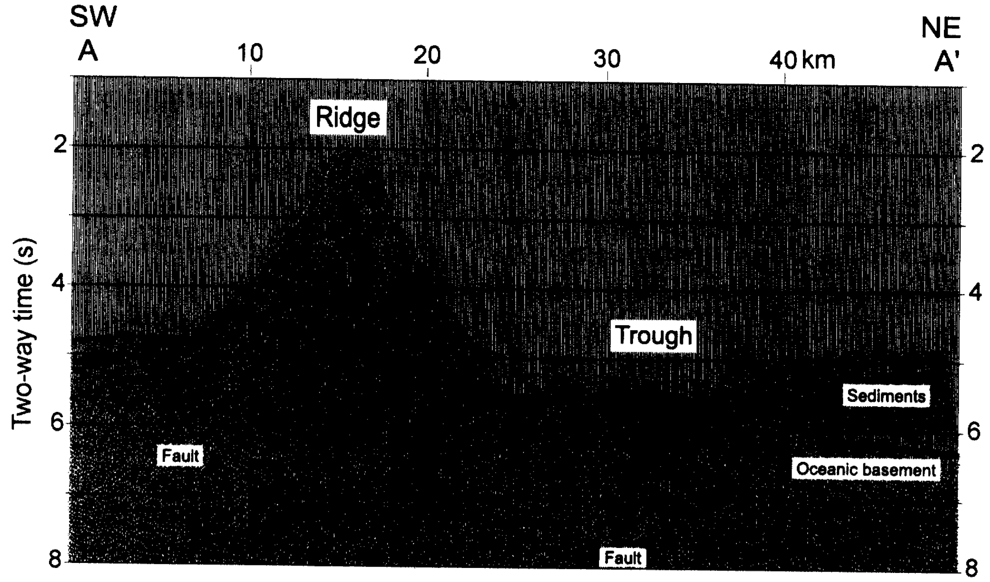


Fig. 3. *Multichannel seismic profile of KSL93-1 across the Shackleton Fracture Zone. The fracture zone comprises a high ridge and a deep trough. See text for interpretation of the profile.*

Phoenix plate including the ridge to the west of the trough is younger than that (28 Ma) of the Scotia plate to the east (BAS Tectonic Map of the Scotia Arc, 1985). The depth difference (about 400 m) of the oceanic basement across the SFZ at both ends on profile KSL93-1 is much larger than that (150-250 m) predicted from age-depth relationships of the ocean floor proposed by several investigators (*e.g.* PARSONS and SCALTER, 1977; COCHRAN, 1986; MARKS and STOCK, 1994). In comparison with adjacent seismic profiles of KSL93-2, KSL93-3, and KSL93-6, the oceanic basement of the NE end of profile KSL93-1 shows almost the same depth with adjacent area, whereas the SW end is shallower (>0.1-0.2 s in two-way travel time). This large depth difference, therefore, seems to be attributed mainly to the uplift of the younger former Phoenix plate, which was probably associated with the forming of the ridge. This view is supported by relatively steep dip (~3°) of the oceanic basement from the western foot of the ridge to the SW end of the profile.

3.3. Deformation in the SFZ

To the northeast of the SFZ ridge, a linear topographic low delineated by 4000 m bathymetric contour is parallel to the ridge (Fig. 1). Profile KSL93-1 shows clearly a deep sedimentary trough below the topography low (Fig. 3). The trough has an asymmetry with steep southwestern flank bounded by a large high-angle fault and relatively gentle northeastern flank with the basement deepened in step by several faults. This morphology of the trough seems to be a half-graben with a large normal fault and several synthetic faults, which may be regarded as a negative flower structure formed in an extensional strike-slip fault. The trough is the site of the SFZ transform system that is a boundary between the Antarctic and Scotia plates.

The thickness of sediments in the trough is up to 2000 m near the southwestern flank. Most part of trough-fill show chaotic internal reflections, except a lenticular sedimentary body on the top of the trough. The lenticular unit with well-laminated reflections is interpreted as sediments deposited by bottom currents flowing along the axis of the trough. Around the trough, a small sedimentary mound and an anticlinal sedimentary cover appear to the east and the west of the trough, respectively.

The seismic profile KSL93-1 shows two phases of deformation around the trough corresponding to the change in tectonic regime (Fig. 3). The former and major deformation is extensional deformation forming the large-scale trough by crustal drop along high-angle faults. The later and weak deformation is compressional deformation forming the contractional structures including a small sedimentary mound and possibly an anticlinal sedimentary cover around the top of the trough.

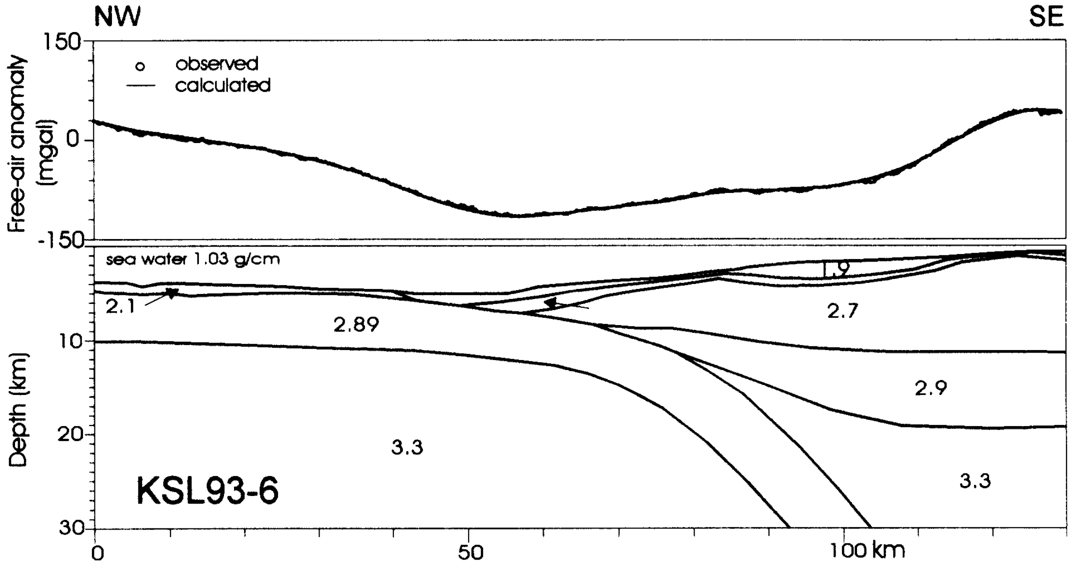
According to previous studies (BARKER *et al*, 1991; LARTER and BARKER, 1991), very important change in mode of Scotia Sea evolution took place at 6 Ma, when the central Scotia Sea as South Georgia block collided with the northeast Georgia Rise and seafloor spreading stopped in Drake Passage. After that time, the Scotia plate has shown a slow westward convergence with respect to the Antarctic plate. Therefore the major extensional deformation in the SFZ is thought to have been generated by transtension associated with strike-slip movement of the during the opening of Drake Passage SFZ before 6 Ma. Recent small-scale compressional deformation was probably formed by more recent convergence between the Scotia and Antarctic plates after 6 Ma. Based on earthquake study, PELAYO and WIENS (1989) suggested that present convergence between the Scotia and Antarctic plates in the Drake Passage region is taken up through diffuse compressional deformation in the passage as well as strike-slip faulting along the SFZ.

Another distinct feature related with the former extensional deformation is the outwardly tilted crustal block on both walls of the trough. At 5 km northeast from the eastern wall of the trough, a large fault offsets the basement and overlying sediments, and the western block of the fault tilts by about 6° clockwise relative to the eastern block. These features are indicative of the uplift of outer blocks accompanied with the dropping of the inner blocks in the trough. This is very similar to the Vening Meinesz's model for the formation of the rift valley (HEISKANEN and VENING MEINESZ, 1958).

4. South Shetland Trench

4.1. Lithospheric structure of the subducting plate beneath the SST

A gravity model of KSL93-6 suggests that the dip of subducting oceanic crust is more than 30° in the shallower part and becomes steep toward the deeper part. On KSL93-5, its subducting angle seems to be at least 25° (Fig. 4). A recent refraction model (GRAD *et al*., 1993) shows that the dip of the subducting plate in the SST is about 25°. Considering their refraction seismic line lies about 150 km southwest of KSL93-6, the difference in subducting angles can be explained by the age difference of the subducting oceanic crusts. A seafloor isochron map (HENRIET *et al*., 1992) shows that the former Phoenix plate is divided into three segments each with a spreading center. The ages of the ocean floor of these segments near the trench become older from 12 Ma to the southwest to 22 Ma to the northeast along the trench as their spreading centers become more distant from the trench. This indicates that the oceanic crust of the refraction model at the trench is younger (12 Ma) than those of KSL93-6 (22 Ma) and KSL93-5 (17 Ma). It is likely that the older,



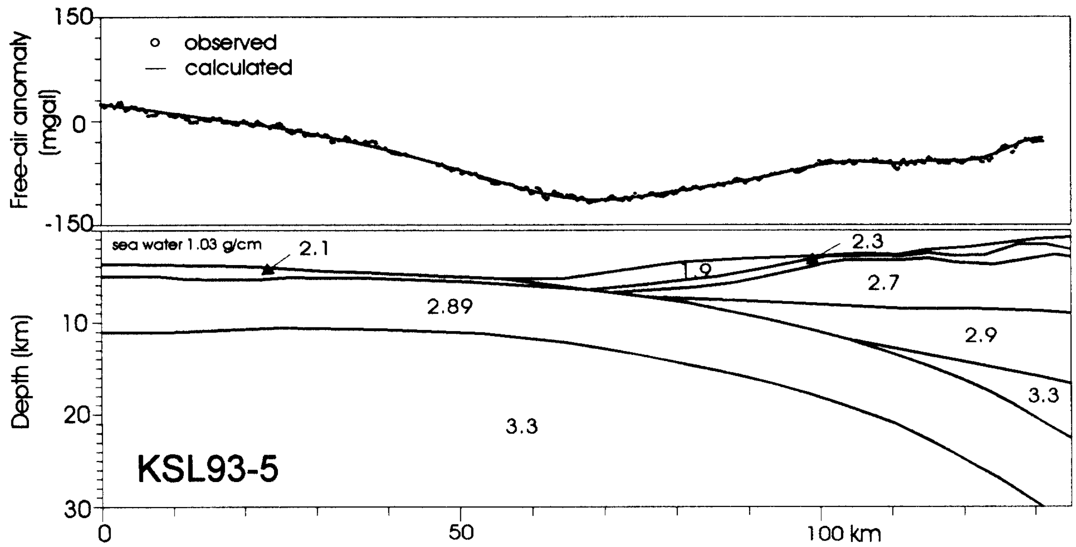


Fig. 4. Gravity models for KSL93-6 and KSL93-5 across the South Shetland Trench, suggesting that the dip of subducting oceanic crust increases toward northeast from 25° in KSL93-5 to 30° in KSL93-6 along the trench.

denser segment to the northwest in the SST has a steeper descending dip of the crust. Kim *et al.* (1995) suggests that the systematic variations of trench morphology from southwest to northeast along the trench are related to the age of the ocean floor, the convergence rate, and the sedimentation in the trench.

4.2. Horst and graben structures and thick trench sediments in the SST

Seismic profile KSL93-6 shows clearly two grabens on the top of oceanic basement in the trench (Fig. 5). A 3 km-wide graben with a vertical displacement of about 600 m occurs beneath the seaward edge of the trench. The other below the toe of the accretionary wedge is separated about 10 km from the previous one. Subduction zones with a horst

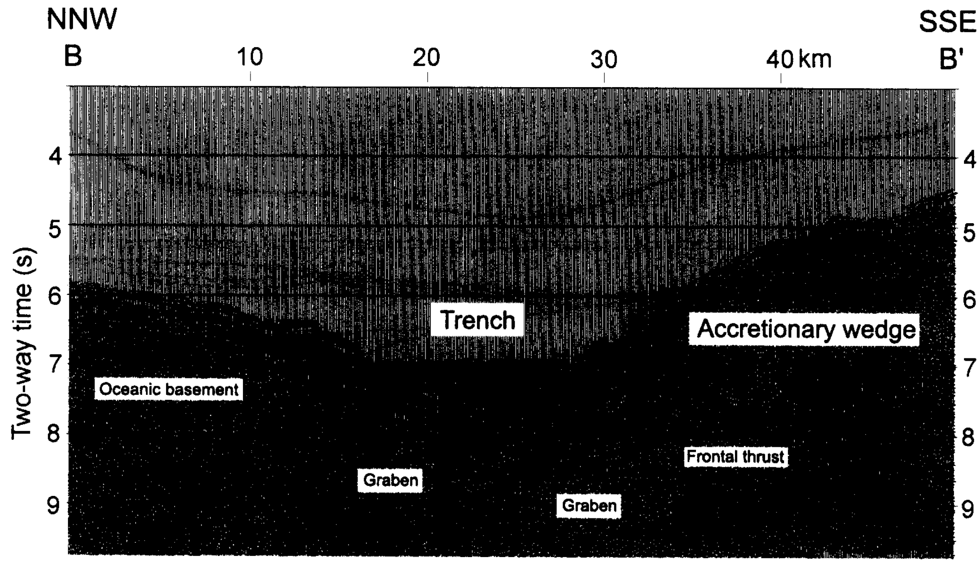


Fig. 5. Multichannel seismic profile of KSL93-6 across the South Shetland Trench. Two large grabens occur on the top of the oceanic crust beneath the trench. The frontal thrust overriding the upper trench-fill sediments cuts though the lower subducted sediments. See text for interpretation of the profile.

and graben structure are observed at virtually all trenches around the Pacific, except where thick sedimentary deposits (greater than 400 m) cover the oceanic plate and fill the trench axis (LUDWIG and HOUTZ, 1979). As the graben structure acts like 'buckets' that fill up with sediments which are carried down the subduction zone, it appears that essentially all the sediments reaching the trench axis are subducted with the descending plate at the trench with well-developed graben if there is no excessive sediment supply from the fore-arc region (HILDE, 1983; RUFF, 1989).

On our profile, thick trench sediments (> 1000 m) cover over the horst and graben structures (Fig. 5). It is very contradictory feature to the role of the horst and graben structures. If the volume of supplied sediment was greater than that of subducted sediments in the SST, thick trench-fill sediments and thick accretionary wedge would be expected. There is no sign of such a high sedimentation rate in the recent geologic history offshore South Shetland Islands. POREBSKI *et al.* (1991) proposed a sedimentation rate of 120 m/my from a piston core data acquired in the SST. MALDONADO *et al.* (1994) referred to a sedimentation rate of 1400 m/my in the Nankai Trough for the SST. Porebski's rate seems to be more acceptable for the SST in comparison with a sedimentation rate of 287 m/my measured at the Chile trench near the Chile Triple Junction (BEHMANN, 1992). Also the strong westward bottom water flow along the trench from the Scotia Sea to Drake Passage through a gap in the Shackleton Fracture Zone was reported (NOWLIN and ZENK, 1988). This strong current is thought to reduce the sediment supply in the SST.

If subduction continues along the SST, the graben structure can provide a mechanism to remove sediments from the trench. Assuming convergence rates of 40–50 km/my averaged over the past 25 Ma (HENRIET *et al.*, 1992) and a series of the grabens with a spacing of 10 km, four to five grabens presumably move down beneath the overriding plate per million years. From preliminary calculations with the profile area of the graben (about 1.8 km^2), the width of trench floor (12 km), and the sedimentation rates (120 to 1000 m/my), total capacity of sediment consumption by the grabens (7.2 to 9.0 km^2/my) should carry most of trench sediment supply (1.4 to 12 km^2/my) down into the subduction zone. Consequently if subduction is still active at the SST, thick trench-fill sediments (> 1000 m) above the horst and graben structures are not expected to occur within the trench. The presence of thick sediments at the SST, therefore, implies that the sediments have accumulated since the cessation of subduction. This suggestion is supported by the disappearance of horst and graben structures on the outer slope of the SST that is quite unexpected in the active trenches. Timing of cessation of subduction is not certain, but it is reasonable that the subduction process virtually ceased at the same time or shortly after the cessation of spreading in Drake Passage at about 4 Ma (BARKER, 1982).

4.3. Compressional deformation in the SST

A frontal thrust that forms the boundary of the trench-fill sediments and the accretional wedge in the SST indicates that the trench is being shortened at present (KIM *et al.*, 1995). LARTER (1991) and MALDONADO *et al.* (1994) argued that the thrust is indicative of the present-day subduction along the trench. However on profile KSL93-6 (Fig. 5), the thrust overriding the upper youngest unit of the trench-fill sediments seems to cut though the lower subducted sediments and reach to the oceanic basement. This feature is somewhat different from the typical frontal trusts observed in subducting trenches that merges into a basal decollement. The frontal thrust on profile KSL93-6 is considered as an indication of the state of stress applied to the trench sediments rather than the movement of the down-going plate. The stress for crustal shortening is believed to come from the current Bransfield Strait extension behind the old island arc rather than subduction at the SST (LAWVER *et al.*, 1996). Bransfield Strait extension is accommodated by diffuse deformation at the former trench in a plate including Drake Passage, the SST, and a part of Bransfield Strait.

5. Conclusions

The multichannel seismic and gravity data in this paper show the crustal structure and tectonic deformation of the SFZ and the SST. The SFZ comprises a high ridge and a deep trough. The gravity models suggest the presence of the anomalous thin crust (about 3 km thick) under the low-density SFZ ridge. The SFZ ridge was probably formed by the uplift of low-density material like serpentinite along the fracture zone. Two phases of tectonic deformation are observed in the SFZ trough. The former deformation forming the large-scale trough was probably associated with transtension along the SFZ during the opening of Drake Passage before 6 Ma. The later small-scale compressional deformation observed around the top of the trough was related with recent convergence between the Scotia and Antarctic plates after 6 Ma.

The gravity models of the SST show that the subducting angle also increases from about 25° in KSL93-5 to 30° in KSL93-6 as the age of the subducting oceanic crust increases from southwest to northeast along the SST. As thick sediments accumulation is not expected in active trenches with a horst and graben structure, the presence of thick trench sediments (> 1000 m) over the horst and graben structure in the SST indicates the cessation of subduction along the trench. Subduction along the SST probably stopped at the same time or shortly after cessation of ANT-PHO spreading at 4 Ma. Compressional push by present-day Bransfield Strait extension probably caused diffuse intraplate compressional deformation in the Drake Passage region, specially in the SST area. This compression may generate the frontal thrust at the toe of the accretionary wedge that deforms both oceanic crust and sediments in the SST.

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